Aerothermochemistry of Turbulent Flows

The following nine papers were presented at the AIAA Aerothermochemistry of Turbulent Flows Conference in San Diego, Calif., December 13–15, 1965. The Organizing Committee of the conference consisted of H. Yoshihara, Chairman, R. vanden Berg, S. C. Lin, W. Nachbar, T. Y. Tong, and F. A. Williams. The review procedure for these papers was handled by Paul A. Libby.

Progress Report on a Digital Experiment in Spiral Turbulence

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Digital hot-wire techniques have been used to measure the tangential variation of the vector mean velocity and the six Reynolds stresses at one radial position in a statistically stationary mixed laminar-turbulent flow between counterrotating concentric cylinders.

INTERMITTENT spiral flow patterns like the one shown in Fig. 1 are known to be typical of transition in circular Couette flow when the two cylinders rotate in opposite directions.[1–4] The spiral band of turbulence rotates steadily at very nearly the mean speed of the two cylinders, so that a given element of fluid near either wall must participate alternately in the laminar and turbulent motions. A question therefore arises as to energy processes that occur near the interfaces separating laminar and turbulent regions of flow.

In 1958, a research program was begun at Graduate Aeronautical Laboratories California Institute of Technology (GALCIT) to study this question experimentally in a large cylinder apparatus using air as a working fluid and hot wires as primary instrumentation. The technique involves repeated sampling of signals from a calibrated multiple hot-wire array so as to obtain an ensemble of values for the instantaneous vector velocity at a large number of points fixed in the rotating pattern. The research has therefore required the breaking of new ground in the application of high-speed sampling and computing equipment to experimental work in turbulence.

The particular flow chosen for detailed study[3,4] is at quite low Reynolds number ($R_0 = 50{,}000$, $R_i = -5{,}600$ based on radius and surface velocity), with air velocities relative to a probe mounted on one or the other cylinders of about 3 to 5 fps. The spiral pattern is left-handed and makes an angle of about 62° with the cylinder axis of rotation.

In the fall of 1962, analog tape recordings were made of signals from a hot-wire array in this flow. About 3500 cycles of the flow pattern were recorded at each of 17 radial positions across the annulus. These analog data have been used directly[3,4] to determine the mean shape of the turbulent region, with the result shown in Fig. 2.

In 1963, electronic data-processing equipment at the Jet Propulsion Laboratory was used to obtain digital samples of the hot-wire voltages at about 60 points in each laminar-turbulent cycle of each analog tape (about 180 million binary bits of information in all). The resulting voltage data were processed once by computer[3] to correct for slight drift and nonlinearity in the recording, playback, and sampling operations. At the same time, calibration data for the hot wires were fitted analytically so as to specify the response to changes in flow speed and direction. A method was also worked out for inversion of this probe-response operator in a computer, i.e., for computation of the instantaneous vector velocity from sampled voltages. The final inversion method consists of a two-stage iteration process and requires about 0.06 sec in an IBM 7094 computer for each vector. The hot-wire probe configuration is a double V array in two planes at right angles, as shown in Fig. 3. The wire coefficients (slope, intercept, and curvature in King's formula based on normal velocity) depend weakly on flow direction. They therefore are evaluated first for the mean flow condition. The two velocity components in the plane of one V are then estimated, assuming the flow to lie in this plane; the lateral component thus obtained is treated as a known velocity normal to the plane of the other V; an improved estimate of the velocity com-

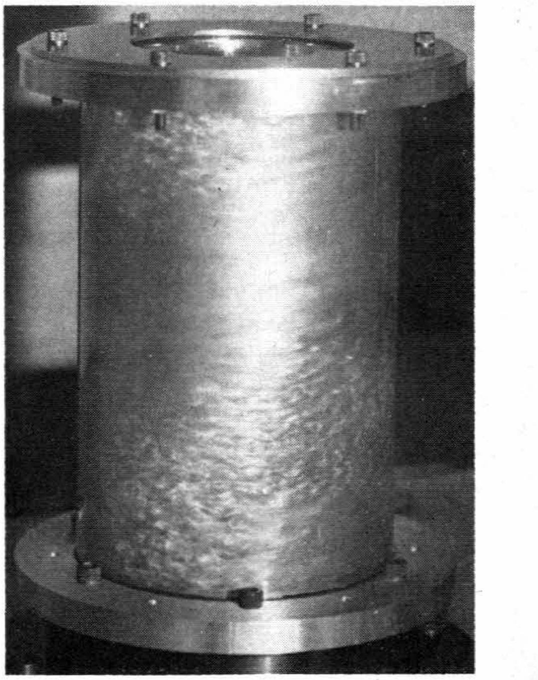

Fig. 1 Right-hand pattern of spiral turbulence in small Couette-flow apparatus. Flow visualization uses suspension of aluminum flakes in silicone oil. Reynolds numbers for outer and inner cylinders (based on radius and surface velocity) are $R_0 = 15{,}900$, $R_i = -5{,}300$.

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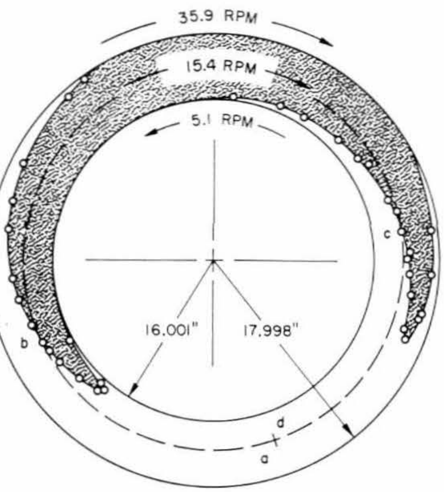

Fig. 2 Cross section showing mean shape of turbulent region at midlength (view looking south in laboratory); radial coordinate slightly distorted for clarity. Reynolds numbers are $R_0 = 50{,}000$, $R_i = -5{,}600$. Note that angular velocity of turbulence is mean of ω_0 and ω_i. Dashed line is locus of measurements in Figs. 4–6.

ponents in the second plane is obtained, and so on. This calculation alternates between the two V arrays until the velocity components no longer change (3 to 5 iterations). The wire coefficients then are revised to correspond to the computer flow direction, and the program loop is repeated (4 to 8 iterations).

The final inversion program was perfected only after more than three years of development. It was checked by processing calibration data in laminar flow, in which case the known velocity magnitudes were recovered within a fraction of 1% and the known flow angles within a fraction of 1°. As applied to sampled tape data, the main program 1) verifies the input data format; 2) computes Nusselt numbers from voltages, 3) computes a nondimensional vector velocity by the method already described, 4) flags each vector as laminar or turbulent by a digital discrimination scheme, 5) edits the flag data for local inconsistencies, 6) writes the velocity data and flags on an output tape, 7) computes for each point in the pattern the ensemble mean of each velocity component (with standard deviation, skewness, and flatness), 8) computes the six components of Reynolds stress, and 9) repeats the last two steps after shifting the velocity data forward or backward within each cycle so as to sharpen one or the other interface position to a statistical discontinuity.

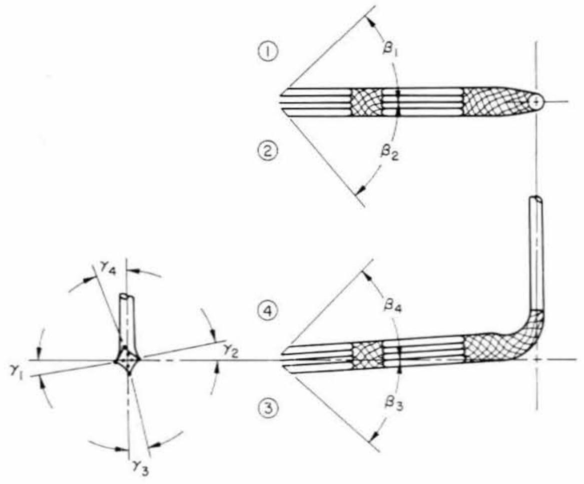

Fig. 3 Probe configuration of four hot wires in double V array.

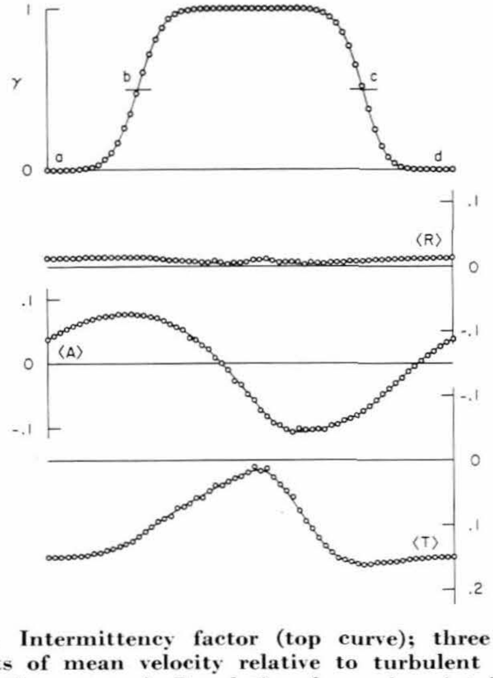

Fig. 4 Intermittency factor (top curve); three components of mean velocity relative to turbulent region (lower three curves). Population for each point is 1667 samples. Components R, T, A in radial, tangential, and axial directions, respectively, are normalized, so that surface velocities (viewed from turbulent region) are essentially + 1.

Data have now been completely processed for one radial position, shown by the dashed circle in Fig. 2 (tape H_0; $r =$ 16.875 in.). The intermittency factor, mean velocities,‡ and Reynolds stresses are plotted in Figs. 4 and 5. In Fig. 6 the flow at this radius is unwrapped, or developed, in order to

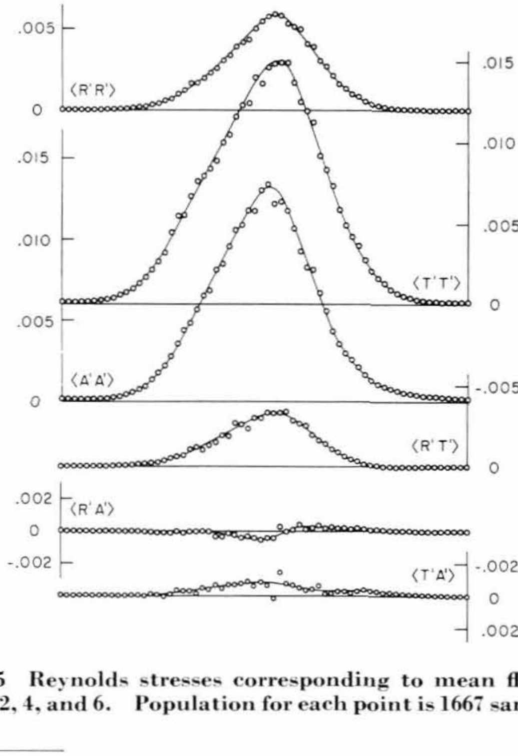

Fig. 5 Reynolds stresses corresponding to mean flow of Figs. 2, 4, and 6. Population for each point is 1667 samples.

‡ The geometric configuration of the probe (a double V array rather than a double X array) is such that the computed radial (axial) velocity includes a small contribution from the radial (axial) gradient of tangential velocity. A correction in the mean for this effect can evidently be made as soon as the digital data have all been processed to the present stage.

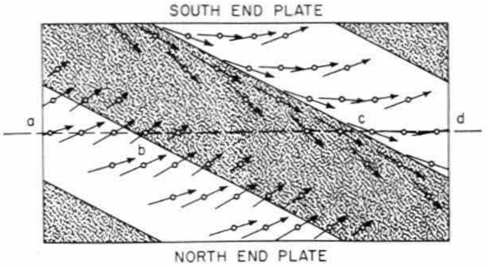

Fig. 6 Mean flow at roughly midgap relative to turbulent region. Velocity is projected on developed plane (view looking radially inward). Dashed line is locus of measurements in Figs. 2, 4, and 5.

show the direction and magnitude of the projected mean velocity relative to the interfaces in a radial view.

From Figs. 4 to 6, two tentative conclusions can be drawn which are unlikely to change as the remaining data are processed.

1. The fluid enters the turbulent region abruptly, but leaves in a grazing direction almost parallel to the interface. In other words, the time available for decay of the turbulence is probably much longer than would be the case if the exit were also abrupt.

2. The mean flow relative to the turbulence has a stagnation point in the interior of the turbulent region. In other words, the mean flow pattern probably resembles the one inferred earlier[1] for a turbulent slug in a pipe. The turbulent energy is a maximum near this stagnation point, and falls rapidly and almost linearly toward the interfaces.

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Turbulence Structure in Free Shear Layers

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The free shear layer in the mixing region of a circular jet has been studied in detail to provide a model for shear flow turbulence. The statistical characteristics of the turbulence can be expressed as kinematic similarity relationships based on the jet diameter and axial distance as length scales, and the inverse local shear as a time scale. The results include averaged properties and probability distributions and moments of the turbulent fluctuations. Spectra and convection measurements suggest that a strong, fluctuating pressure field surrounds the shear layer. The existence of this field provides explanations for discrepancies found between local mean and turbulent convection velocities and for radial variations in the probability distributions. These results provide a physical model. Mathematically, the shear layer has been represented by a random distribution of discrete travelling vortices and studied on a computer. The statistical properties found with the two models are compared.

Introduction

Mixing flows are of interest and practical importance in almost all processes involving heat and mass transfer, including a range of applications from combustion and chemical reactions to water treatment and boundary-layer control. High mixing rates are normally associated with turbulent motion, and one is concerned both with methods of achieving high turbulence levels and with relating mixing rates to the characteristics of the turbulent flow. Classical models suggest that turbulence consists of a wide spectrum of eddy sizes existing together with a continuous transfer of energy from larger to smaller scale motions. The largest eddies extract energy from the mean flow while the smallest convert it into molecular motion or heat. The best experimental evidence for this model has been obtained in regions of homogeneous decaying turbulence produced behind a regular grid at relatively low flow speeds.[1] Although fair agreement exists between observed mixing rates and predictions for this type of flow with zero or low shear, the mixing rates are not, in general, very high since the turbulence is relatively weak. Thus this type of turbulence is often more of theoretical interest than of practical importance in mixing.

Free shear layers provide regions of strong turbulence in which relatively high mixing rates are attained. The turbulence may originate in the rolling up of a thin vortex sheet, which results in eddies that may be thought of as groups of vortices retaining some form of coherent motion within the group. An individual eddy, which can be defined as a region across which velocity fluctuations remain partly correlated, can be called statistically stable if it retains some of its statistical characteristics for a duration long enough to measure them, although the interactions between its constituent vortices will inevitably result in continuous modification of its structure. Thus, eddy structure will have a reality that

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